Electrochemical Capacitance-Voltage Analysis of Delta-Doped Pseudomorphic High-Electron-Mobility Transistor Material

C. E. Stutz
B. Jogai
David C. Look
Wright State University - Main Campus, david.look@wright.edu
J. M. Ballingall
T. J. Rogers

Follow this and additional works at: http://corescholar.libraries.wright.edu/physics

Part of the Physics Commons

Repository Citation
http://corescholar.libraries.wright.edu/physics/51

This Article is brought to you for free and open access by the Physics at CORE Scholar. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of CORE Scholar. For more information, please contact corescholar@www.libraries.wright.edu.
Electrochemical capacitance-voltage analysis of delta-doped pseudomorphic high electron mobility transistor material

C. E. Stutz
Solid State Electronics Directorate, Wright Laboratory, WL/ELR, Wright-Patterson AFB, Ohio 45433

B. Jogai and D. C. Look
University Research Center, Wright State University, Dayton, Ohio 45435

J. M. Ballingall and T. J. Rogers
Electronics Laboratory, Martin Marietta Corp., Syracuse, New York 13221

(Received 4 January 1994; accepted for publication 22 February 1994)

This work shows how electrochemical capacitance-voltage (EC-V) measurements can be used to evaluate delta-doped pseudomorphic high electron mobility transistor material. These EC-V measurements are compared with magnetic field-dependent Hall effect (M-Hall) measurements and a self-consistent Poisson/k·p calculation of the band structure and electron concentration. The EC-V technique clearly delineates the cap layer, the delta-doped layer, and the InGaAs channel layer, whereas the M-Hall method characterizes only the cap and InGaAs channel layers. The amount of electron charge seen by the EC-V and M-Hall measurements show good agreement with theory.

Conventional capacitance-voltage (C-V) measurements, in which a stepped reverse-bias voltage is used to successively deplete small regions of a semiconductor layer, have long been used to determine dopant concentration profiles in relatively thick semiconductor materials. By applying the so-called depletion approximation to Poisson’s equation, an apparent concentration \( N_{\text{true}} \) = \( C^2 / \epsilon \epsilon_0 (dC/dV) \) at an apparent depth of \( x_{\text{true}} = c/C \) provides a profile which approximates the true profile quite well except for regions in which \( N_{\text{true}} \) varies significantly within a Debye length. Fortunately however, even when \( N_{\text{true}} \) is distorted, the apparent charge differential \( dQ = eN_{\text{true}} dx_{\text{true}} \) is equal to the true charge differential \( dQ = eN_{\text{true}} dx_{\text{true}} \), as is easily shown from the above equations, so that the integrated charge of the measured C-V profile is correct.

In recent years, the conventional C-V method has been applied both to AlGaAs/GaAs heterostructure junctions and also to sheet-charge (“delta-doped”) layers. In the latter case, when electrons exist in quantized levels, the Debye-length limitation no longer holds, and the C-V resolution is related to the wave-function extent. Since present day high-speed devices like pseudomorphic high electron mobility transistors (pHEMTs) contain a highly doped cap layer, which leads to diode breakdown for high reverse biases, a different technique called electrochemical C-V (EC-V) is applied. The EC-V method substitutes stepped surface etching for stepped reverse biasing. The whole experiment is carried out at a low bias, so that breakdown is not a problem. Even though the experimental procedure differs from conventional C-V measurements, the analysis is basically equivalent. Here we demonstrate, for the first time to our knowledge, that the EC-V technique can separate the cap layer, the delta layer, and the InGaAs channel layer [containing a two-dimensional electron gas (2DEG)]. The EC-V results agree with theoretical modeling for the combined sheet charge of the delta and 2DEG layers. The results are also consistent with magnetic-field-dependent Hall-effect (M-Hall) data, which can characterize the cap and 2DEG regions.

The EC-V measurements were made by using a PN4200 BIO-RAD system with 0.1 M Tiron as the electrolyte and a 3-mm-diam sealing ring. These conditions gave relatively good uniform etch rates. Bias conditions were carefully chosen so that leakage currents were minimized for accurate measurements. The system was calibrated with conventional Hall measurements using thick (∼1 μm) uniformly doped molecular beam epitaxial (MBE) GaAs:S i layers doped at \( 3 \times 10^{18} \) cm\(^{-3} \), so as to minimize errors due to depletion. The thickness was calibrated against reflection high-energy electron diffraction (RHEED) oscillations carried out in the MBE system.

Figure 1(a) shows the pHEMT structure with the delta-doped layer in the barrier separated from the channel by 45 Å. The listed thicknesses and concentrations are nominal. Figure 1(b) gives theoretical results of the energy-band and electron-concentration profiles. The electron distribution and potential were calculated from a self-consistent k·p formulation. The electron wave functions, from which the electron distribution is calculated, were obtained from the k·p model. The Hartree part of the potential was calculated from the Poisson equation and the exchange correlation part from density functional theory within the local-density approximation. The model assumes that all the shallow donors are ionized. Note that the integrated charge is larger in the well (2DEG) than in the delta-doped region for the present structure, which has a 45 Å spacer.

Figure 1(c) shows the EC-V results for the sample of Fig. 1(a) (solid line). In Fig. 1(c) we note the cap layer at 300 Å and then an asymmetric structure is seen between 500 and 700 Å. We believe the small shoulder of the asymmetric peak on the shallow side represents the delta-doped barrier region and the larger peak at 640 Å is due to the 2DEG in the well region. This explanation agrees with the theoretical profile of Fig. 1(b) in a qualitative sense. We also have included mea-
Table I. The electron concentration, in units of $10^{12}$ cm$^{-2}$, measured by the EC-V and M-Hall techniques, compared to theory for a pHEMT with a 45 Å spacer layer.

<table>
<thead>
<tr>
<th>Region</th>
<th>EC-V</th>
<th>M-Hall</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap</td>
<td>$5.4 \pm 2$</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>δ layer</td>
<td>...</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>2DEG</td>
<td>$3.1 \pm 0.2$</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>δ+2DEG</td>
<td>$4.5 \pm 0.3$</td>
<td>...</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Note that in the present case we have not etched through the cap by the time the depletion region is through the 2DEG. In cases for which the cap is etched through at this point, the measured charge in the delta-doped region will be lower due to the lack of screening from the electrons in the cap. In other words, to accommodate the potential at the etched surface, some of the charge in the delta will have to flow to the surface states if these states are not filled with cap electrons.

Room temperature M-Hall measurements were carried out using magnetic fields of 2, 10, and 16 kG. The technique is described elsewhere, but basically can separate the carrier concentration and mobilities in two conductive layers, unlike conventional Hall-effect measurements. In this case we determine concentrations and mobilities $n_{2DEG}$, $\mu_{2DEG}$, $n_{cap}$, and $\mu_{cap}$, but not the parameters in the delta since its electrons have too low a mobility ($\sim 100$ cm$^2$/V s) to be observed. Results are given in Table I, and it is seen that $n_{2DEG}$ agrees well with theory. On the other hand $n_{cap}$ usually cannot be determined with good accuracy by the M-Hall technique. Fortunately, $\rho_{cap}=(en_{cap}\mu_{cap})^{-1}$ is determined more accurately, and since $\mu=1500 \pm 500$ cm$^2$/V s for nearly all GaAs cap layers, we can determine $n_{cap}$ from this value of $\mu_{cap}$ and the measured $\rho_{cap}$. This technique leads to satisfactory agreement between measurement and theory for $n_{cap}$, especially since the theory does not include the possibility of GaAs/Al$_x$Ga$_{1-x}$As interface charge for this particular case.

In conclusion we have compared EC-V measurements with M-Hall measurements and theoretical calculations to show the usefulness of the EC-V technique for exploring the properties of delta-doped pHEMT material. The EC-V measurements can delineate the cap, delta-doped, and 2DEG regions. They are also useful for determining the total doping in the delta-doped and In$_x$Ga$_{1-x}$As regions, and for qualitatively showing the amount of charge transferring from the delta-doped layer to the 2DEG region.

The authors would like to thank R. E. Sherriff for valuable discussions. This work was partially supported by the Advanced Research Projects Agency (ARPA) monitored by the U. S. Air Force under MIMIC Contract No. F33615-91-C-1784, the Air Force Office of Scientific Research (AFOSR), and by the U. S. Air Force under Contract No. F33615-91-C-1765.

Measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate the individual delta and 2DEG contributions for 45 Å spacer material.

The data from a nominal 180 Å spacer sample that shows two completely separated peaks at 600 and 810 Å depth, respectively. These data demonstrate that we are actually able to delineate the delta-doped layer in the barrier (at 600 Å) and the 2DEG in the well (at 810 Å). To compare the 45 Å layer with theory we arbitrarily chose to integrate the charge from the concentration minimum ($dN_{cap}/dz_{cap}=0$) between the cap layer and the delta-doped layer effectively to infinity for both the theoretical and measured results, since effects from the doped cap are assumed negligible beyond this minimum. Using this method the total delta plus 2DEG integrated charge is consistent for the above theoretical and measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate the individual delta and 2DEG contributions for 45 Å spacer material.

The data from a nominal 180 Å spacer sample that shows two completely separated peaks at 600 and 810 Å depth, respectively. These data demonstrate that we are actually able to delineate the delta-doped layer in the barrier (at 600 Å) and the 2DEG in the well (at 810 Å). To compare the 45 Å layer with theory we arbitrarily chose to integrate the charge from the concentration minimum ($dN_{cap}/dz_{cap}=0$) between the cap layer and the delta-doped layer effectively to infinity for both the theoretical and measured results, since effects from the doped cap are assumed negligible beyond this minimum. Using this method the total delta plus 2DEG integrated charge is consistent for the above theoretical and measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate the individual delta and 2DEG contributions for 45 Å spacer material.

The data from a nominal 180 Å spacer sample that shows two completely separated peaks at 600 and 810 Å depth, respectively. These data demonstrate that we are actually able to delineate the delta-doped layer in the barrier (at 600 Å) and the 2DEG in the well (at 810 Å). To compare the 45 Å layer with theory we arbitrarily chose to integrate the charge from the concentration minimum ($dN_{cap}/dz_{cap}=0$) between the cap layer and the delta-doped layer effectively to infinity for both the theoretical and measured results, since effects from the doped cap are assumed negligible beyond this minimum. Using this method the total delta plus 2DEG integrated charge is consistent for the above theoretical and measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate the individual delta and 2DEG contributions for 45 Å spacer material.

The data from a nominal 180 Å spacer sample that shows two completely separated peaks at 600 and 810 Å depth, respectively. These data demonstrate that we are actually able to delineate the delta-doped layer in the barrier (at 600 Å) and the 2DEG in the well (at 810 Å). To compare the 45 Å layer with theory we arbitrarily chose to integrate the charge from the concentration minimum ($dN_{cap}/dz_{cap}=0$) between the cap layer and the delta-doped layer effectively to infinity for both the theoretical and measured results, since effects from the doped cap are assumed negligible beyond this minimum. Using this method the total delta plus 2DEG integrated charge is consistent for the above theoretical and measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate the individual delta and 2DEG contributions for 45 Å spacer material.
1 M. Sundaram and A. C. Gossard, J. Appl. Phys. 73, 251 (1993).